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March 18, 2002

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Dear Dr. Yu:

Attached is the Administrative Report for the Georgia Tech Center of Excellence in Rotorcraft Technology (CERT) for the Period 1Feb 2001 to 31Jan 2002.. A brief summary of each of the 12 tasks is included. I apologize for the late submittal. I didn't realize it was due prior to the end of the year.

Daniel P. Schrage

Dr. Daniel P. Schrage
Director, Georgia Tech CERT

Task #: GT 1.1
Title: Active Rotorcraft Blade Tips for Tip Vortex Core Modifications
PIs: D. Stefan Dancila, Narayanan M. Komerath and Lakshmi N. Sankar

Thrust Areas: Efficient, Low Noise Rotors; Smart and Composite Structures

Objectives: The research objectives of this effort are to understand the physical processes that influence the formation of the tip vortex of a rotor in advancing flight, and to develop active and passive means of weakening the tip vortex during conditions when strong blade-vortex-interaction effects are expected. A combined experimental, analytical, and computational effort is being employed. Specifically, the following efforts are being pursued:

a.) Analytical evaluation and design of combined elastic tailoring and active material actuators applicable to rotor blade tips.
b.) Numerical simulations of active and passive tip devices
c.) LDV Measurement of the near and far wake behind rotors in forward flight

CFD Studies:

Two of the principal investigators (Dancila and Sankar) are collaborating on the modeling of rotors in hover and forward flight. For rotors in hover, the NASA Ames/U. S. Army TURNS code is being used, and enhanced. For rotors in forward flight, a seventh order accurate overset grid based method is being used. During the first year, the CFD code TURNS was modified and used to study the wake structure in hover for a baseline rotor configuration with an AR of 6. Initial convergence difficulties encountered have been resolved. Typical results, obtained for or a collective angle of attack of 8 degrees, a tip Mach number of 0.306 and a Reynolds number of 1.4 10^6 by using a grid of 135x75x50 are shown in Fig. 1. These results indicate that the tip vortex can be resolved in considerable detail. A number of modifications to the original flow solver were necessary to resolve this vortex. These modifications, along with correlations for the velocity field behind a rotor tested by Ken McAlister will be submitted as a paper to a forthcoming AIAA meeting (Reno 2003).

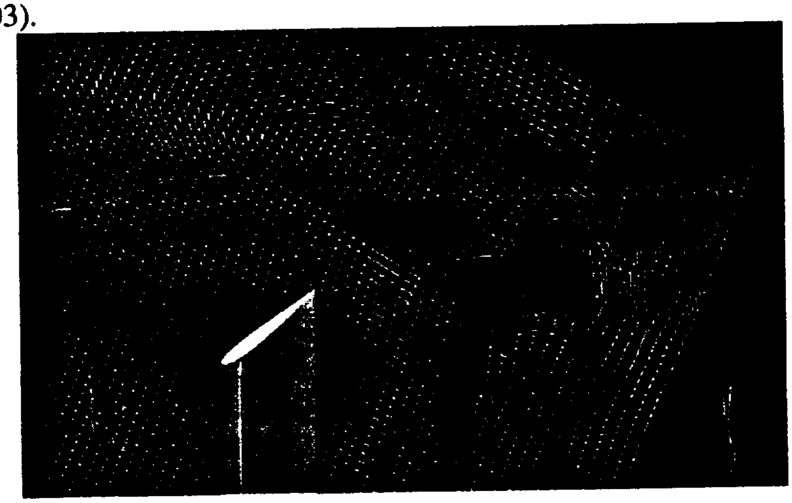

Figure 1. Self-Generated Vortex at a Vortex Age of 60 degrees behind an AR=6 blade.

The TURNS code has also been modified so that it can handle spoilers, and turbulators. A sample configuration being studied is shown in figure 2 below.

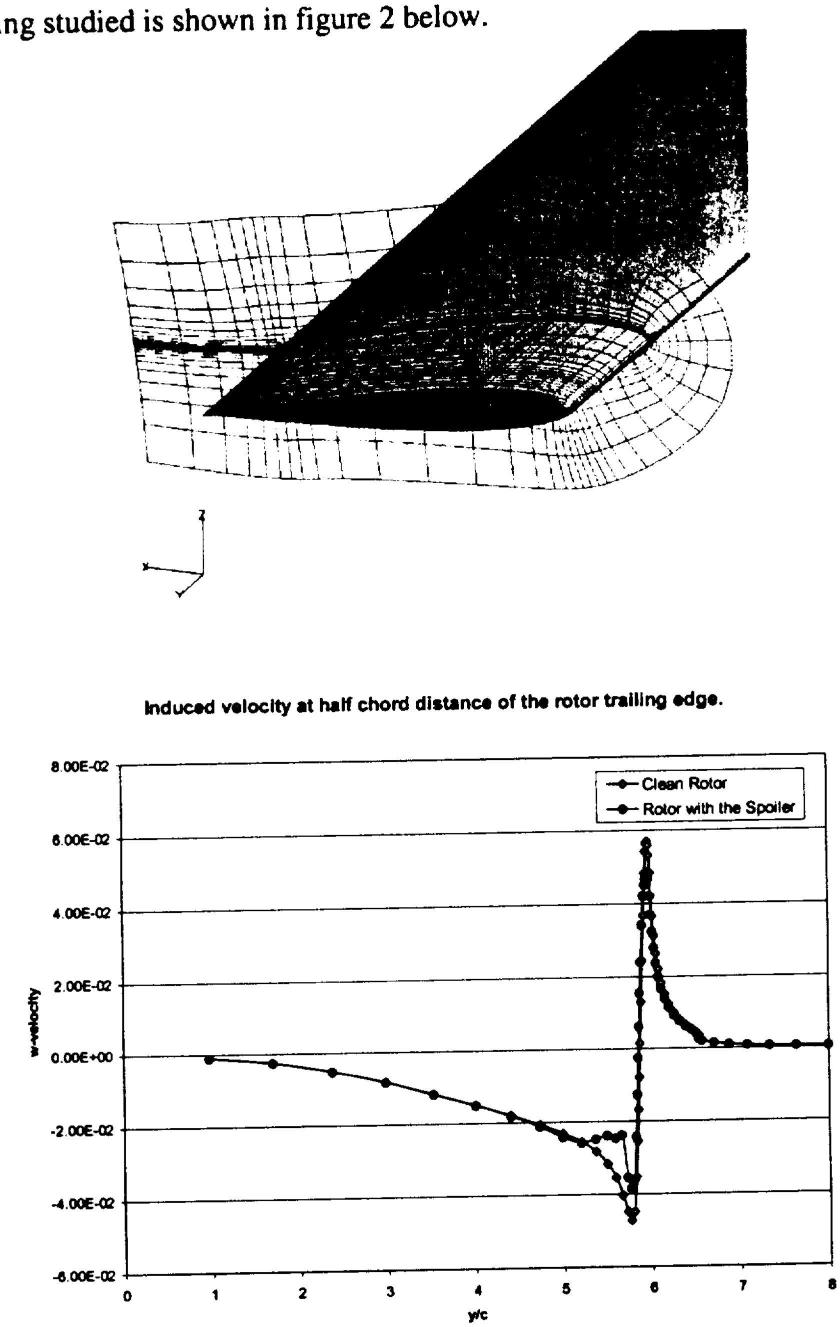

Figure 2. Effects of a Spoiler on the Induced Velocity Field Associated with the Tip Vortex

Experimental Studies:

Experiments conducted by Oliver Wong focused in detail on the formation of the top vortex at the tip of a rectangular rotor blade operating in low-speed forward flight. The results showed that a substantial part of the vorticity in the shear layer rolling up over the tip in the first 40% of the blade chord actually escaped the tip vortex, and merged with structures forming inboard. Thus control areas constructed in the cross-flow plane at outboard part of the blade trailing edge still captured much the circulation associated with the peak bound circulation, but similar areas further downstream captured a much lower value of circulation. This answered a mystery found by Mahalingam in analyzing the results from various rotor blade and fixed-wing experiments in the literature – where the tip vortex strength was seen to be consistenly limited to about 40% of the value expected from the blade peak bound circulation, or the gradient of circulation near the blade tip. Wong's data also provides a clearer picture of the process by which the rotor tip vortex core diameter appears to grow – this issue is being investigated further as it provides a new avenue to perform first-principles prediction of tip vortex growth rate.

These data complete an extensive knowledge base on a sharp-edged, square-tipped rotor blade. Using the blade-construction techniques being developed by Prof. Dancila, a new rotor with blade geometry identical to this rotor, was built and safety-tested in the tunnel. This will serve as the baseline rotor for future tests, to compare vortex structure and formation processes with newer blades with systematically modified tips.

Tailored Composites/Active Structures Component:

A baseline test rotor has been manufactured using an integrated CAD design and CAM and a second rotor with similar configuration and rounded tips is currently manufactured. Composite skins have been manufactured for a composite rotor, using an aluminum mold manufactured using CAD/CAM. The use of CAD/CAM in conjunction with rapid prototyping techniques has been explored for the efficient manufacturing of blade tip sections of complex geometry and with internal channeling for the provision of blowing.

A piezoelectrically actuated flap design for a rotor blade tip is investigated and implemented. The flap is supported on a star-beam hinge. This configuration allows for high axial and bending hinge stiffness and low torsional stiffness, providing an elastic flap support that carries the centrifugal flap load without friction, unlike a conventional hinge. Piezoelectric bender actuators are used in a leaf-spring configuration and oriented/supported such that centrifugal loading produces an amplification of actuator output. This actuation concept is experimentally investigated on a centrifuge test stand.

Task#: GT 1.2
Title: First Principles based Modeling of Rotors in Hover, Forward Flight and Maneuver
PIs: L. N. Sankar, Stephen Ruffin, Dave Peters

Thrust Areas: Low Vibrations, Efficient Low Noise Rotors

Background and Technical Barriers: During the past two decades, much progress has been made in modeling rotorcraft wake, and in predicting airloads and noise characteristics. A variety of computational tools, ranging from lifting line analyses to first-principles based Navier-Stokes analyses, have become available. It is now possible to get reasonably accurate solutions for rotors in hover[i] and in forward flight[ii,iii]. First principles based calculation of rotors in maneuvers is considered feasible but has not been attempted, largely because of the prohibitively expensive cost of such simulations.

Despite the progress that has been made, first-principles based methods have not found acceptance within the engineering community. Several technical barriers need to be overcome for such acceptance to be gained. Much work remains to be done in improving the formal spatial and temporal accuracy of the simulations, and in reducing the numerical dissipation and dispersion errors in these methods. The turbulence models and transition models used in these simulations are rudimentary, and often give incorrect or conflicting results[iv]. Forward flight and maneuvering calculations need to be done for several blade revolutions because of the need for trimming the rotor, thus requiring large computer time.

In many applications, lifting line theories will continue to be used in conjunction with dynamic inflow theory and/or free wake models. To date, only a limited attempt has been made to compare the inflow velocities in forward flight, computed using CFD, dynamic inflow, and free wake approaches. For maneuvering flights, such comparisons are nonexistent. It is important to compare these complementary approaches to enhance the simulations and improve the inflow models.

Objectives

The overall goal of this work is to develop a first-principles based Navier-Stokes methodology capable of efficiently and accurately predicting rotor airloads and noise characteristics in hover, forward flight, and maneuvers. The following specific objectives are proposed:

a) Improve the existing 3rd, 5th and 7th order spatial accuracy algorithms in the NASA Ames (OVERFLOW) and Georgia Tech (GTNS3D) family of rotor aerodynamics analyses[3]. Make commensurate improvements in the temporal accuracy, boundary condition treatment, load integration, and in the calculations of metrics (cell volumes, cell surface areas).

b) Investigate transition and turbulence models that are appropriate for forward flight and maneuvers.

c) Develop adaptive, embedded grid (CHIMERA) methods for tracking pockets of vorticity for large distances.

d) Reduce the overall CPU time through the use of low fidelity solutions (e.g. Lagrangean wake, potential flow) wherever possible.

e) Validate the improved algorithms using NASA Ames (Piziali), UTRC (Lorber- UH60A), U. S. Army (TRAM, HART data, McAlister's wake data), and flight test data.

f) Compare the inflow velocity distributions from the simulations with Dr. Peter's dynamic inflow theory, for selected cases. Many comprehensive codes use dynamic inflow theory for its generality, efficiency, and accuracy. Identify regions of discrepancy, and make improvements to the flow solver and the dynamic inflow theory, as appropriate.

g) Perform Collaborative studies with industry and government researchers on the performance, airload and noise characteristics of current generation (UH-60, Apache, Comanche, V-22) and next generation (e.g. quad-tilt rotor) configurations.

Reviewer's Comments

At the kick-off meeting the following comments and suggestions were made:

"We recommend that the investigators calculate airfoil drag and pitching moment and validate these results with experimental data. We recommend investigation of level flight and hovering conditions before moving on to maneuvering flight conditions. Please coordinate with industry, the other two RCOE centers, and also government labs. Are the computational resources enough? Much emphasis of the task is on computational techniques, how about physics of the problem or modeling issues (for example, rotor wakes)?"

These comments (with the exception of the comment on CPU resource needs) have been addressed in the first year's work.

Work done during the First year

In response to the reviewer's suggestions, the static lift, drag, and pitching moment characteristics of a NACA 0015 airfoil were studied. Satisfactory agreement with experiments was observed. Dynamic stall simulations were also done. The dynamic stall results for were, however, found to be less satisfactory. The shed vortices were in general weaker, and the hysteresis loops were found to be smaller than in the experiments. Grid size sensitivity, time step sensitivity, and turbulence model sensitivity studies are being done to further understand this problem. Results from this study have been submitted as an abstract to the European Rotorcraft Forum, in collaboration with ONERA researchers who have been studying the same problem.

A sixth order accurate central difference scheme, and an 8th order accurate central difference scheme have been developed for solving the 3-D Navier-Stokes equations, and implemented in the NASA Ames/U. S. Army TURNS code. This methodology was applied to the UH-60A rotor in hover. Very good agreement with experiments was observed for the rotor performance. These calculations were presented at the 2001 AHS Annual Forum, and at the 2002 AHS Aeromechanics Specialists Meeting. The enhanced version of TRUNS code has been distributed to the industries. This technology transfer activity was funded in part by RITA.

A seventh order accurate upwind scheme has been developed, and implemented into Georgia Tech 3-D Navier-Stokes analysis. Preliminary results have been obtained for the Caradonna-Tung rotor in hover. At this writing, this analysis is being applied to UH-60A rotor in hover and forward flight. The hover results were presented at the 2002 AHS Aeromechanics Specialists Meeting.

Work Planned for the Second Year

The seventh order accurate upwind scheme will be further validated for rotors in hover, and forward flight. A version of this algorithm will be implemented in TURNS, and tested.

In forward flight, grid adaptation or an overset grid is necessary to capture the wake accurately. We will attempt to include an overset grid in the 7^{th} order accurate upwind analysis, and determine if this strategy can resolve the tip vortices for the first two revolutions.

[i] Ahmad, Jasim U., and Strawn, Roger C., "Hovering Rotor and Wake Calculations with an Overset-Grid Navier-Stokes Solver," Proceedings of the American Helicopter Society 55 th Annual Forum, Montreal, Canada, May 25-27, 1999.

[ii] Nathan, Hariharan and Sankar, L., "A Review of Computational techniques for Rotor Wake Modeling," AIAA paper 2000-0014, 38th AIAA Aerospace Sciences Meeting, Reno, NV.

[iii] Hariharan, N.S. and Sankar, L.N. "First-Principles Based High Order Methodologies For Rotorcraft Flowfield," Proceedings of the American Helicopter Society Annual Forum, 1999, pp 1921-1933.

[iv] Srinivasan, G. R., Ekaterinaris, J. A., and McCroskey, W. J., "Dynamic Stall of an oscillating Wing, Part I. Evaluation of turbulence Models," Computers and Fluids, Vol. 24, No. 7, pp. 833-861.

Task #: GT 1.3
Title: Simulations of Unsteady Flow-Rotor Interactions to Predict Dynamic Loading in a Turbulent Environment
PIs: M. J. Smith, S. Menon

Thrust Areas: Safe/Highly Reliable, Low Vibration/Noise

Objectives

a) Identify sources of error in current turbulence models in unsteady flows using large-eddy simulations as numerical experiments.
b) Evaluate the impact of errors in turbulence models on unsteady load predictions.
c) Evaluate the influence of free-stream turbulence on the load predictions.
d) Develop method(s) to correct the most egregious of these errors and/or to investigate alternate, more accurate, higher-order turbulence models.
e) Validate the simulation and turbulence closure methodologies using data on a generic rotor /wing.
f) Implement improvements into an existing Navier-Stokes rotor solver and correlate predictions using additional rotor experimental data on UH-60A.

Reviewer's Comments on Objectives:

At the kick-off meeting, the following suggestions were made by the reviewers:

LES has never been applied yet to transition problems and no one has yet run LES on a 3D wing-tip vortex roll-up problems. Isn't this task too ambitious? There is some concern about (lack oj) validation effort. NASA Langley recently (Jan. 01) conducted a

These comments are being addressed, and minor changes have been made to the approach as discussed below.

Work done during the First year

1. We contacted Jim Thomas at NASA-LaRC and obtained the report of the turbulence workshop. We are using the results of the workshop to guide selection and development of turbulence models.
2. We performed a literature search on CFD applications to the rotorcraft industry to determine the models currently utilized (and the state of the prediction capability).
3. LES method development has proceeded. The code employs finite volume scheme and runs in a parallel environment, MPI. . A "Cut-Cell Method" that is based on moving *only* the body on a fixed rectangular background grid is being coded to handle moving the grid. A static semi-infinite flat plate was first simulated with the code to validate the boundary layer predictions of the LES code.
4. In order to enhance validation efforts, the NACA0015 static and dynamic stall experiments were chosen as the baseline geometry (Piziali, NASA TM 4632, USAATCOM TR 94-A-011). This ties in with other rotorcraft efforts in dynamic stall and will provide both 2D and 3D effects to address the initial reviewer concerns. The LES code, as well as a structured

(ENS3DAE) and two unstructured (Cobalt and FUN3D) RANS codes, have been chosen for these studies.

5. Initial verification began with the study of the impact of the trailing simulation on static and dynamic results using the RANS codes. Grid impact (C vs. H vs. O) was also evaluated for both RANS and LES.
6. Currently, the solutions for static and pitching semi-infinite NACA0015 wings are being obtained for correlation with experimental data and comparison of LES and RANS models. These results will be presented at the meeting in April. Work is focusing on the semi-infinite models (2D) to begin this study. We will begin 3D simulations when the 2D results are completed, probably late in Year 2.
7. The reviewers raised the question of transition model. The transition model is a very complex problem, and so it was decided that evaluating both turbulence and transition is outside of the scope of this task's resources. The focus of the project is now limited to turbulence models. A limited number of calculations are being done under Task 1.2 for oscillating airfoils, where two existing transition models (Eppler, Michel) are being addressed. These findings will be separately reported under the subject tasks. Positive findings from Task 1.2 on transition models will be evaluated on selected simulations on this project.
8. In order to optimize the budget and time constraints of this project, DoD HPC time was requested and received from the Army contact, Dr. Roger Strawn. Two of the three students have recently obtained clearance to utilize these computers. The clearance status of the remaining student is proceeding.

Task#: GT 2.1
Title: Efficient and Affordable Joining of Composites
PIs: E. A. Armanios, A. Makeev and D. S. Dancila

The load transfer mechanism in a generic joint such as the single-lap is effected through interlaminar peel and shear stresses. Their distributions within the overlap region follow a boundary layer form. An effective approach to improving lap joints is to address the cause of these boundary layer type interlaminar stress distributions. That is, reduce or reverse the peel stress to compressive stress and redistribute the intensity of both transverse normal and shear stress over the entire length of the overlap. Corrugation of the joint overlap interface was proposed as an effective means in achieving efficient stress redistributions. Furthermore, corrugation of the interface region would not alter the existing layup and is applicable to all interfaces. Stress enhancement mechanism in corrugated overlap joint would be a result of the non-planar surface creating a tortuous path for crack propagation.

The corrugated design concept was achieved by inserting metallic wires along the 90/90 interface of the quasi-isotropic adherends as shown in Fig. 1

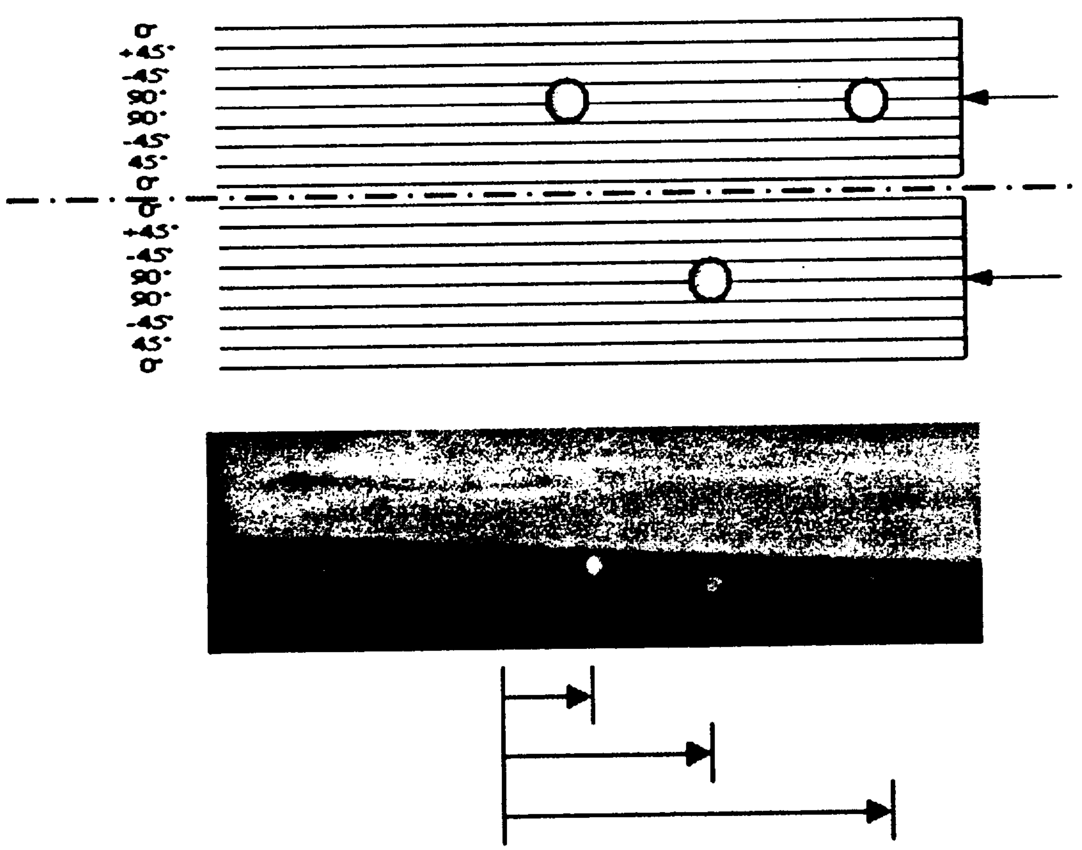

Fig. 1 Corrugated-interface Lap Joint

Four corrugated configurations with wave numbers ranging from ½ to 1½ were tested under monotonic tension. Eight joints from each type were manufactured and tested. The failure loads were recorded as well as the failure modes using a high-speed camera. Compared to the unmodified joints, the failure modes of the corrugated designs switched from interfacial debonding to combined fiber pullout and breakage initiating at the wire insert location. The change in failure mode did not yield consistent or appreciable improvement in strength as shown by the results in Table 1.

Table 1 Average Strength values

Specimen	Ave. Strength (N)	Std. Deviation (N)
Unmodified	16.62	1.16
Type 1 (1/2 w)	17.24	0.54
Type 2 (1/2 w)	16.26	0.62
Type 3 (1 w)	16.42	1.23
Type 4 (11/2 w)	15.67	0.89

An Alternative method of creating corrugated interfaces is being investigated along with a nested overlap concept. An analytical modeling of the nested concept shows a reversal of interlaminar peel stress to compression. This is bound to result in a significant improvement in strength.

Task#: GT 3.1
Title: Phenomenological and First-Principles based Models of Complete Helicopters
PIs: L. N. Sankar, M. J. Smith, D. Peters

Thrust Areas: Affordability, Low Vibrations, Safe/Highly Reliable

Objectives

a) Develop Navier-Stokes methods and improvements that complement existing techniques for modeling complex rotorcraft configurations.
b) Validate the methodologies using GIT, NASA Langley, and U. of Maryland experimental data.
c) Improve limitations in the numerical modeling by improvements in turbulence modeling, algorithm stencil, and vortex tracking.
d) Extend unstructured Navier-Stokes methodology to perform loosely and tightly coupled (static and dynamic) aeroelastic analyses for linear and nonlinear structural models
e) Identify the limitations of the methodology in correctly capturing surface deflections and loads associated with the nonlinear aerodynamics (vortex & viscous behavior) by comparing with experimental data.
f) Investigate the impact of different types of interactional aerodynamics on noise, structural fatigue, and handling qualities using experimental data. Identify areas where smart structures and aerodynamic controls may be effective in flow control.
g) Use the CFD simulations as a test-bed for developing and validating phenomenological approaches for interactional aerodynamics and empennage positioning (e.g. Dr. Dave Peter's dynamic inflow theory providing upwash/downwash, combined with a simplified representation of the empennage as lifting line/vortex surfaces).

Reviewer's Comments on Objectives:

At the kick-off meeting, the following suggestions were made by the reviewers:
"Please provide details on solution adaptive unstructured grid implementation. Solution adaption on tetrahedral meshes is a very difficult problem. Not enough justification why this approach will succeed compared to others previously tried and failed. Transition model is not addressed."

These comments are being addressed, and minor changes have been made to the approach as discussed below.

Work done during the First year

1. During the first year, we evaluated four unstructured grid based flow analyses for their suitability in modeling rotor airframe interactions:

a) NASA Langley Solver USM3D: We have acquired this flow solver, along with associated grid generators (Vgrid) and flow visualization solver (VPlot). This methodology has impressive capabilities and has already been validated for a number of external flow configurations. The fact that a grid generator and the flow visualization solver were both available was also helpful. However, at this writing, we only have access to this code as executable modules. The present approach requires modifications to the source code for embedding structured CHIMERA grids, or placing body force terms to simulate a lifting line representation of the rotor. For this reason, we are not using USM3D analysis in our studies at this time.

b) Air Force Research Lab (AFRL) Analysis (Cobalt): This analysis was also acquired, and considered as a starting point for our research. The present investigators are very familiar with this methodology. One of the investigators (Sankar) directed the Ph. D. dissertation of a contributor to the Cobalt analysis (Dr. Robert Tomaro), and assisted in the implementation of an implicit time marching scheme, and a high order spatial approximation scheme in Cobalt. The second investigator (Dr. Marilyn Smith) has extensively used this analysis to study flow over oscillating airfoils and wings. Georgia Tech has Cobalt only in executable form due to distribution restrictions. This analysis methodology is now being developed and supported by a private firm started by Cobalt's original author Dr. Strang. While Dr. Strang has expressed his willingness to assist us in using this analysis for modeling and understanding rotor-airframe interactions, this will require a financial support on our part to support Dr. Strang's efforts. For these reasons, we are not using Cobalt as the primary solver.

c) NASA Langley Solver FUN3D: We have acquired this analysis from NASA Langley Research Center. This analysis is available in source code form. In addition to web documentation and NASA-LaRC technical support, the code has been extremely well written in an easy-to-follow, modular form. Single processor and multiple processors are both supported, although problems exist with the Portland Group compilers. Finally, this analysis can model both incompressible and compressible flow problems. For these reasons, we are presently using FUN3D as the starting point for our studies. NASA Langley researchers are also fully supporting this code, and upgrades scheduled in the next year include grid adaptation and algorithm improvements.

In addition, the following additional analyses are being performed:

d) Georgia Tech Overset Rotor-Body-Interaction Technology (GTORBIT): This methodology is based on Dr. Nathan Hariharan's thesis work, and is being extended under Task 1.2. This methodology can handle overset grids, and automatically generate the domain connectivity information at each time step. The flow solver is of seventh order spatial accuracy in the interior. At the regions where the grids overlap, under Task 1.2, we are investigating the use of high and low order interpolation schemes to understand which schemes best conserve vorticity, mass, momentum, and energy, when flow information is being interpolated from grid to grid. Finally, this method allows embedded overset grids, which may be used in an automated form to track vortices. This feature has already been demonstrated for tip vortex capturing from fixed wings (2000 AHS Forum paper by Hariharan and Sankar), and will be used or adapted in the present approach (See reviewer's comments on solution adaptive grid).

e) Prof. Ruffin's Cartesian-grid-based Unstructured Solver: The present investigators also closely work with Prof. Ruffin, the Co-PI for Task 1.2. In his approach, the flow field is divided in Cartesian rectangular (or brick-like) cells. Near body surfaces, the cells are automatically subdivided into finer cells, while retaining their brick-like shape. Cells may be added as needed in the interior, to track phenomena of interest such as tip vortices. This analysis thus already uses solution-adaptive grids (See Reviewer's comments, expressing concerns on this issue).

2. The present researchers acquired body-fitted grids for the NASA Langley ROBIN fuselage and rotor configurations (courtesy of Dr. Tadghighi, Boeing Mesa), and detailed model geometry and measured surface pressure data (courtesy of Dr. Henry Jones of U. S. Army). At this writing, simulations are being done for this configuration with the FUN3D code, and will be presented at the oral briefing in April. Coupling of the code with the ABAQUS finite-element code has also begun to permit the code to perform buffet analysis.

3. Additionally, Prof. Smith has obtained the circular cylinder basic geometry and flow conditions from Prof. Long of PSU to perform similar computations with FUN3D to compare with his code results. Computational time has been obtained on the DoD parallel computers courtesy of Dr. Roger Strawn, and these computations are also underway for presentation in April. The computational size and time requirements of the problem prohibited computation on the GIT Aeroelasticity Lab SGI, and the Beowulf cluster was not available due to compiler problems yet to be resolved by the Portland Group.

4. Calculations have been done with the GTORBIT code for a hemisphere cylinder configuration tested at Georgia Tech, with and without the rotor. Spatially fifth order accurate solutions have been obtained (similar in quality to Dr. Hariharan's results in his dissertation).

5. The reviewers raised the question of transition model. The transition model is a very complex problem, and is outside of the scope of this task's resources. Task 3.1 (Smith and Menon) as part of fundamental investigations into transition will provide insight into the turbulence modeling issues for the rotor and fuselage that will be utilized in these results. A limited number of calculations are being done under Task 1.2 for oscillating airfoils, where two existing transition models (Eppler, Michel) are being addressed. These findings will be separately reported under the subject tasks. Positive findings from both Task 3.1 on turbulence models and Task 1.2 on transition models will be incorporated into the codes utilized in this task as they become available.

Task#: GT 5.1
Title: Elastically Tailored Smart Composite Blades
PIs: E. A. Armanios, D. S. Dancila and O. A. Bauchau

The family of cross sections, developed under the previous task, has been investigated using the finite element based cross-section analysis code developed by Bauchau. The basic mechanism hinges upon augmenting the extension-twist coupling of closed sections having high torsional stiffness by integrating them with elastically tailored strip arms. Various combinations of closed section diameter, number of arms and geometry have been analyzed. A typical section and the analysis results are shown in Figs. 1 and 2.

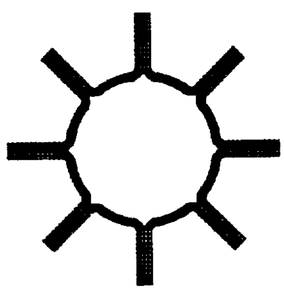

Fig. 1

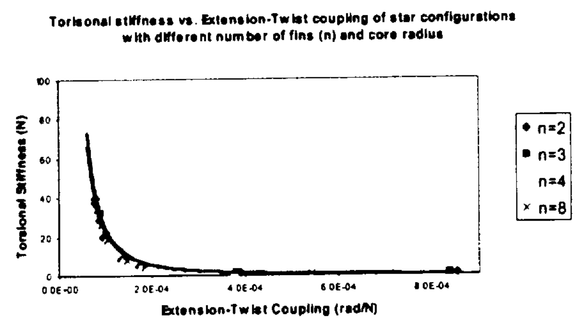

Fig. 2

The analysis resulted in the fact that the enclosed area is the main variable determining the behavior of the section. This observation has been confirmed with various other strip and closed section combinations. Based on these results, new concepts that utilize elastomeric joining allowing for additional degree of freedom in tailoring the cross section have been explored. The analysis showed the significance of enclosed area is the major factor controlling the overall behavior of the section.

An alternative means to tailoring the stiffness and extension-twist coupling would be to allow span wise variations in the cross-section. This concept includes making use of closed and open sections in innovative ways to overcome the constraints set by the enclosed area. Various models are being studied.

Task#: GT 5.2
Title: Damage Tolerance Analysis of Stiffened Composites and Rotor Hubs
PIs: E. A. Armanios, A. Makeev and A. Badir

One of the major sources of failure in composite structures is delamination initiating from stress concentration sites such as ply drop or a matrix crack. Accurate modeling of the stress state and fracture modes is essential for damage tolerance analysis. Conventional local finite element modeling does not result in accurate prediction of the stress state at the delamination front. The predictions of the finite element based techniques depend upon the crack increment step size, and generally are not convergent. Existing approximate elasticity closed-form models do not accommodate laminates with tapered geometry such as composite flexbeams in rotor hub arms.

Cost effective and accurate models for elastic analysis of composite structures can be developed by applying boundary element techniques. The boundary integral equations represent a closed-form model that does not require additional differentiation to obtain a solution. Therefore, a coarse mesh and low order elements resulting in small systems of linear algebraic equations are expected to provide accurate predictions.

The current focus of work under this task is the development of a simple methodology for applying boundary element modeling to the delamination analysis of laminated composite structures. A simple model based on 2D boundary integral formulation for anisotropic elasticity problems was developed. As shown in figures, models with small number of degrees of freedom accurately predicted the interlaminar stresses and energy release rate components for glass – epoxy laminates of simple tapered geometry.

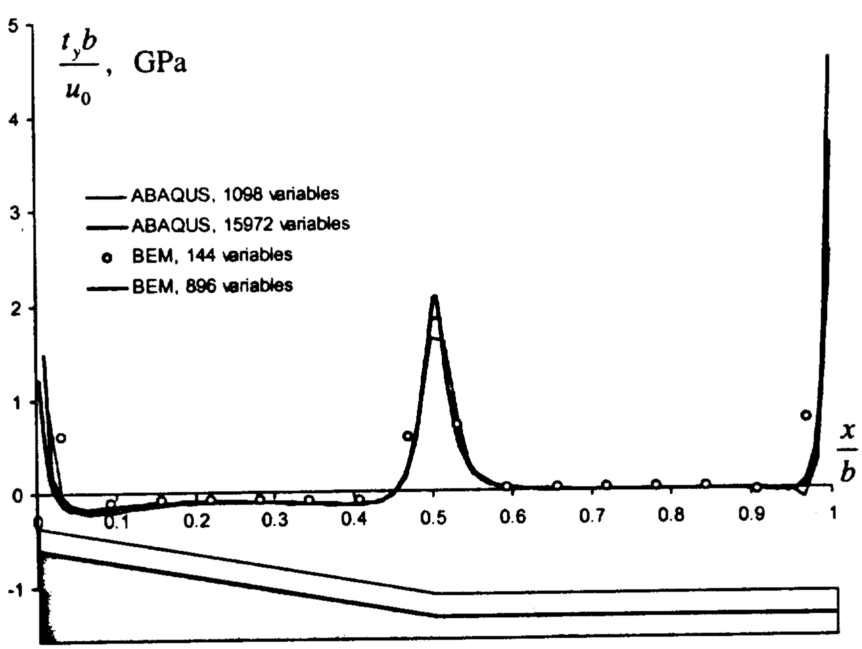

Fig. 1 Comparison of Interlmainar Peel Stress Predictions

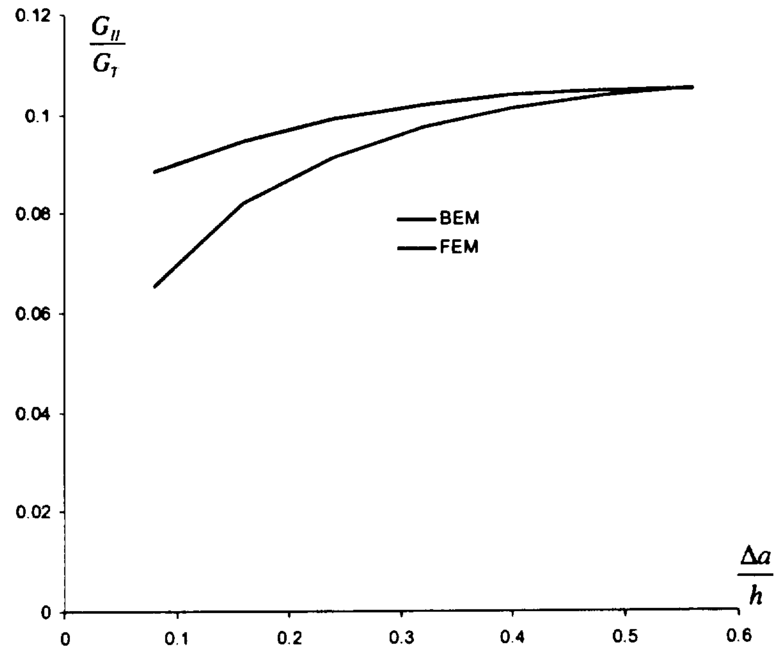

Fig.2 Convergence of Energy Release Rate Mixed-mode Ratio with Crack Step Size

The next phase of the research will be devoted to the development of efficient boundary element code capable analyzing large systems. A parametric study will be carried to establish the benefits of the boundary element method compared to the finite element techniques for fracture mechanics analysis of composite laminates.

Task#: GT-5.3

Title: Composite Beam Cross-Sectional Optimization

PIs: V. V. Volovoi, Research Engineer, and D. H. Hodges, Prof., co-PIs

This task capitalizes on high fidelity analysis tools for composite beams that were developed in-house for the past ten years. These analysis tools have been recently successfully tested for "industrial strength" applications under a companion RITA task.

Based on recommendations from the first year review the following thrust areas were identified:

1. Consult the industrial partners in order to establish "best practices" in rotor blade design
2. Start with a realistic blade section and take into account existing manufacturing constraints as much as possible
3. Set up a relatively simple parametric optimization problem around the baseline and complete it before proceeding to more challenging problems (such as topology optimization)

Progress in 2001:

1. **Industry interaction**: all three major helicopter manufacturers (Boeing, Bell, and Sikorsky) were visited and extensive discussion with the rotor design groups was conducted. Based on this exchange, the guidelines for the example problem were worked out as well as recommendations for the future improvements. This entailed:
2. **Computational Environment/Realistic Baseline:**
   A. Create a stand-alone parametric model: Effective optimization requires a stand-alone geometry definition, since external use of any commercially available computer-aided design (CAD) software would significantly slow down the process. Even for a relatively small number of design variables, relying on the external means for geometry definition would be prohibitively expensive from the computational standpoint. Therefore, a stand-alone fully parameterized model without the external use of any CAD software has been constructed. Available in-house C-language routines that are based on NURBS curves were used for geometry definitions. These routines are flexible enough to accommodate realistic cross-sectional geometry.
   B. The optimization is expected to be quite efficient since a preprocessor with embedded parametric geometric model along with meshing and VABS analysis module are incorporated together in an automatic manner. A single module is created for multiple runs of optimization procedure. Output of the mesh preprocessor is provided for input of meshing process and output from the meshing module is also passed as input of VABS analysis process in a single program. Only a relatively few top-level design variables that control variation in geometry and material properties are required as input. All

intermediate design variables and transformations are handled automatically.

C. The baseline is modeled using the NASA preliminary design report for a composite XV-15 rotor blade. With the outer shape of blade as fixed, the thickness of each element and spar location can be changed parametrically. Caution has to be observed in order to model changes in the thickness of the laminates in a physically sound manner, especially when the radius of curvature is small (such as at the leading edge). A methodology is proposed that preserves the local material density of the ply. This leads to a consistent variation of the ply thickness with local radius of curvature.

3. Optimization example: A relatively simple optimization problem is posed, one with a clear physical meaning. The distance between the shear center and the quarter chord is considered as an objective function. The prime purpose of making the shear center as close as possible to the quarter chord while avoiding or minimizing the elastic couplings. If the objective is achieved, the use of non-structural weights can be minimized or eliminated altogether. Ply angles, ply thickness and spar locations are chosen as design variables. In this stage of the modeling the number of plies is fixed in order to restrict the problem to continuous design variables. The bending and torsional stiffnesses from the baseline model are designated as target values, upper and lower bounds of which are treated as constraints. ADS (Automated Design Synthesis)* has been chosen to as an optimization tool. ADS is capable of solving general nonlinear constrained optimization problems and is flexible enough to test various optimization techniques.

**Vanderplaats, G N. and Sugimoto, H., 1986, "A General-Purpose Optimization Program for Engineering Design", Computers and Structures, Vol 24, pp13-21*

Task#: GT 8.1
Title: Wakes of Rotorcraft Maneuvering in Ground Effect
PIs: N.M. Komerath, A.T. Conlisk

Objectives
This task is to develop detailed physics-based modeling to capture the essential features of ground–effect flows and their effects on rotorcraft, in both quasi-steady state and maneuvers.

Review Panel Comments
"One real practical problem is rotor/airframe design to avoid handling qualities problems near the ground. So, recommend to address this issue in the later years. Wake roll-up modeling is important and please clearly address this issue. How does this free wake model compare with other schemes? Any validation effort for OGE cases? Need to focus the task and please clearly identify the objectives. Please contact A. Egolf at Sikorsky for similar work (moving ground motion)."

Progress in Year 1 :
Response to Comments: Discussions with T. Alan Egolf at Sikorsky and identification of issues had preceded the proposal. This collaboration continues in both the RCOE Task and a RITA project focused on the more applied issues of handling qualities in near-ground flight. As suggested by the Review Panel, the initial work under this RCOE project has focused on capturing the wake rollup process.

Experimental Studies: The PhD thesis of Catherine Matos was completed, on the problem of rotor wake-lifting surface interactions, and the genesis of uownward steady and unsteady loads on a surface placed below the rotor. The results are directly of use in interpreting observations of the ground effect experiments. Two tunnel entries were completed in 2001 with a new ground plane set-up, capturing wake behavior over a range of low forward speed conditions (hover is not a valid test condition in the wind tunnel as presently configured), with and without ground planes in the vicinity. These tests identified 3 test regimes

a. High advance ratio – wake interaction does not produce rolled-up ground vortex. In our case this is for $\mu > 0.08$, valid down to ground clearance of 0.736 rotor diameter.
b. Moderate advance ratio: $0.05 < \mu < 0.08$ a large rolled-up vortical structure is formed at the front base of the rotor wake impingement region. In this regime, the presence of the ground plane causes an increase in the level of "vortex wander" relative to cases where the rotor is isolated in the tunnel. However the upstream vortical structure and the wake trajectory appear to be otherwise steady in a time frame phase-syncronized to the rotor.
c. Low advance ratio $\mu > 0.05$ Discrete, steady rolled-up structure replaced by feedback of discrete vortices to tip path plane. Flow visualization indicates that this condition should produce unsteadiness at roughly 1/3 per rev.

Further studies of these phenomena will use hot-wire anemometry and instrumented ground planes, to confirm hypotheses regarding the origin of non-periodicity.

Analytical Studies: The presence of the ground considerably affects the performance of a rotor. Initial calculations have been made in hover and the results show that since the ground must be a streamline, the rotor wake tends to rapidly expand as it approaches the surface. This alters the wake velocity, the induced velocity in the plane of the rotor, and, therefore, the rotor thrust and power. Ground effect in hovering flight has been examined by several authors either experimentally or theoretically by means of the method of images. In our theoretical model the rotor wake is dominated by the influence of tip vortex. The ground effect on hover is analyzed, to start with, by considering an image of the rotor tip vortex to satisfy the zero normal velocity on the ground. The image wake is assumed to exist below the ground plane and the circulation is in the opposite sense. We considered a few turns of the helical tip vortex. Our model agrees well with the experimental data by Light (1993).

During the next six months, the wake computation will be extended to forward flight. The hover model must be modified through representing the rotor wake by a few turns of the helical tip-vortex and beyond this the wake is represented by a cylindrical sheet of vorticity extending to the ground. An image of this rotor wake with respect to the ground plane will be considered to take into account the ground effect on helicopter performance.

Task #: GT 8.2
Title: Limit Detection and Limit Avoidance Methods for Carefree Maneuvering
PIs: Drs. J.V.R. Prasad and A.J. Calise

Background: A multitude of operational limits constrain the performance and effectiveness of rotorcraft. The responsibility for limit detection and avoidance has historically rested with the pilot. Moreover, many limits are difficult to detect until they have been exceeded. Effective systems for limit detection and avoidance would lead to reduction in pilot workload, and improvements in safety, reliability, maintainability, survivability and mission effectiveness.

Under the previous rotorcraft center effort, a novel method was developed in which a 'dynamic trim' method and off-line trained neural nets were used in conjunction with a variable force-feel system to give the pilot a tactile cue of the distance to the most critical limits. Piloted simulation evaluations of the method using the Boeing simulators showed effective increase in both usable agility and safety.

The present task deals with further development of the limit detection and avoidance method using adaptive neural nets to account for model uncertainty in the dynamic trim predictions and to develop algorithms for transient limit detection and avoidance. Both piloted simulation evaluations and flight testing using the R-50 helicopter test bed are planned.

Objectives: The primary research objectives of this task are:

a) Develop adaptive algorithms for prediction of limit parameters that reach limit boundaries during dynamic trim.
b) Develop algorithms for prediction of limit parameters that reach limit boundaries during transient part of the response.
c) Develop approaches to combine pilot cueing and limiting using AFCS for envelope protection.
d) Carry out simulation and flight test evaluations in collaboration with industry and government labs.
e) Investigate potential application of the envelope limiting algorithms to UAVs using the R-50 helicopter test bed at Georgia Tech.

Accomplishments during '01:

1. Developed an innovative adaptive limit parameter prediction method using artificial neural networks.
2. Carried out simulation evaluations of the adaptive algorithms using the Generalized Tilt Rotor (GTR) simulation model for angle of attack and load factor limiting.
3. Developed a method for extraction of dynamic trim maps directly from time response data.
4. Carried out simulation evaluations of an approach for limiting using the automatic flight control system for UAV applications.

Plans for '02:

1. Integrate the transient limit detection method being developed by Prof. Joe Horn of Penn State with our adaptive approach and carry out batch simulations.
2. Develop a methodology for combined pilot cueing and limiting through the flight control system.
3. Carry out simulation and flight test evaluations of envelope limiting using the AFCS on our R-50 helicopter test bed.

External Interactions :

1. We are currently working with the Boeing Helicopters under the HACT program for transitioning of our envelope limiting methods.
2. Under a student grant, we are currently working with NASA Ames researchers (Mr. Matt Whalley, Dr. Mark Tischler and Mr. Bill Hindson) on in-flight evaluations of tactile cueing using the RASCAL aircraft.
3. Collaborating with Prof. Joe Horn of Pennsylvania State University on transient limit detection and avoidance.

Publications during '01:

<u>Journal Papers:</u>

1. Horn, J., Calise, A.J. and Prasad, J.V.R., "Development of Envelope Protection Systems for Rotorcraft," <u>Journal of the American Helicopter Society</u>, January 2001.

<u>Conference Papers:</u>

1. Yavrucuk, I. and Prasad, J.V.R., "Automatic Limit Detection and Avoidance for Unmanned Helicopters," Proceedings of the 57th AHS Forum, Washington, DC, May 9-11, 2001.
2. Yavrucuk, I., Prasad, J.V.R. and Calise, A.J., "Adaptive Limit Detection and Avoidance for Carefree Maneuvering," Proceedings of the 2001 AIAA Atmospheric Flight Mechanics Conference, Montreal, Canada, August 6-9, 2001.

<u>Patents:</u>

1. Calise, A.J., Prasad, J.V.R., Horn, J., "Method and Algorithms for Neural Network Based Automatic Limit Prediction and Avoidance," Patent No. US 6332105B1.

Task #: GT 9.1.
Title: Deformable Wake Dynamics for Maneuvering Flight Simulation
PIs: Drs. J.V.R. Prasad and D.A. Peters

Background:

It is well recognized for some time that the wake distortion effects are the primary source of the off-axis response behavior observed in maneuvering flight. Several methods have been proposed for modeling of wake distortion effects using simple empirical corrections to comprehensive CFD models. Some of the empirical approaches proposed to correct the off-axis predictions are very limited in scope and, in general, they are not applicable to the entire flight envelope. Comprehensive CFD models are computationally expensive and are not suitable for flight simulation and control law development applications. In contrast, the finite state dynamic inflow models developed in the late 80s, which are routinely used in rotorcraft industry, can easily be combined with other aeroelastic and flight dynamic models for stability and control analysis and for real-time simulation. Development of accurate models to capture the essential physics of wake distortion effects on the flow behavior at and off the rotor are some of the technology barriers for development and evaluation of model decoupling flight control laws and for effective use of piloted simulation for various aircraft subsystem development and pilot training.

Under the previous rotorcraft center effort, a novel method was developed by combining results from the vortex tube theory with the finite state dynamic inflow models for modeling of wake distortion effects. Only steady state maneuvers and inflow at the rotor were considered in that effort. The current task deals with further development of finite state dynamic inflow models for capturing the dynamic wake distortion effects during maneuvering and transitional flight and for prediction of inflow off the rotor, especially at the empennage during maneuvering flight.

Objectives: The overall research objectives of the task are:

a) Development of finite state inflow models to model dynamic wake distortion effects for maneuvering and transitional flight.
b) Development of models for inflow off the rotor.
c) Correlations with available windtunnel and flight test data.
d) Integration of inflow models with a comprehensive flight simulation program, such as the FLIGHTLAB, and carry out batch and piloted simulation evaluations.
e) Transition of inflow models to industry and government labs.

Accomplishments during '01:

1. Formulated a reduced order dynamic wake distortion model in terms of wake longitudinal and lateral curvatures, wake skew and wake spacing as states.
2. Extracted time constants associated with the dynamic wake distortion model for maneuvering and transitional flight from hover by combining results from free wake analysis, vortex tube analysis and finite state inflow theory.
3. Implemented the dynamic wake distortion model into the GENHEL simulation program and carried out correlations using the Black Hawk helicopter test data for longitudinal and lateral cyclic doublet input maneuvers from hover.

Plans for '02:

1. Develop dynamic wake distortion models for maneuvering and transitioning from forward flight.
2. Carry out extensive correlations with flight test data.
3. Develop reduced order models for inflow off the rotor and carry out simulation evaluations using the GENHEL flight simulation model.

External Interactions:

1. We are currently teamed with Boeing (Dr. Shantha Kumar and Mr. Dave Miller) on a proposed RITA task for integration of our new inflow model into the FLYRT simulation model.
2. We have been collaborating with Dr. Bob Ormiston and Dr. Mark Tischler of AFDD, Ames Research Center. We received the Black Hawk helicopter flight test data from Dr. Mark Tischler for model validation.
3. We have been collaborating with Mr. Dave Mitleider of Boeing, Mesa in transitioning of our wake distortion models into the Boeing simulation models.
4. We have been collaborating with Dr. John Berry of AMCOM, Huntsville, Dr. Jerry Higman of ATTC and Dr. Chengian He of ART.

Publications during 2001:

Journal publications:

1. Krothapalli, K., Prasad, J.V.R. and Peters, D.A., "Rotorcraft Inflow Modeling For Maneuvering Flight," Journal of the American Helicopter Society, April 2001.

Conference Papers:

1. Prasad, J.V.R., Fanciullo, T., Zhao, J. and Peters, D.A., "Towards a High Fidelity Rotor Inflow Model for Maneuvering and In-Ground Effect Flight Simulation," Proceedings of the 57th AHS Forum, Washington, DC, May 9-11, 2001.
2. Basset, P-M., Heuze, O., Prasad, J.V.R. and Hamers, M., "Finite State Rotor Induced Flow Model for Interferences and Ground Effect," Proceedings of the 57th AHS Forum, Washington, DC, May 9-11, 2001.
3. Iboshi, N., Nagashima, T. and Prasad, J.V.R., "Experimental Validation of an Inclined Ground Effect Model," Proceedings of the 57th AHS Forum, Washington, DC, May 9-11, 2001.
4. Peters, David A., Morillo, Jorge A., and Nelson, Adria M., "New Developments in Dynamic Wake Modeling for Dynamics Applications," Proceedings of the 57th Annual Forum of the American Helicopter Society, Washington, D.C., May 9-11, 2001.
5. Prasad, J.V.R., Zhao, J. and Peters, D.A., Modeling of Rotor Dynamic Wake Distortion during Maneuvering Flight," Proceedings of the 2001 AIAA Atmospheric Flight Mechanics Conference, Montreal, Canada, August 6 – 9, 2001.

6. Prasad, J.V.R., Zhao, J. and Peters, D.A., "A Study on Dynamic Wake Distortion Effects during Helicopter Transient Maneuvering Flight," Presented at the Ninth International ARO Worksop on Aeroelasticity of Rotorcraft Systems, Ann Arbor, MI, October 22-24, 2001.

Task #: GT 9.3
Title: Robust and Adaptive Flight Control.
PI's: A. Calise and JVR Prasad

This project deals with exploiting and advancing recent developments in robust and adaptive control for the purpose of designing highly adaptive control systems for rotorcraft. The primary motivation is high bandwidth design for future UAV applications. This requires that we treat both parametric uncertainty and unmodeled dynamics in a single framework, together with address such issues as data latency and actuation limits. Parameter uncertainty has long been a motivation for developing adaptive controllers. However, adaptive processes are even more vulnerable to unmodeled dynamics, data latency and actuation limits than are non-adaptive controllers.

A primary accomplishment this past year is the development of two new approaches to adaptive control that permits adaptation to both parameter uncertainty and unmodeled dynamics[1,4]. This has been achieved by avoiding the use of adaptive observers. We have developed two novel architectures, and have evaluated these approaches both in simulation and flight tests[4]. These experiences have revealed that while we are able to reproduce in flight most of the results we obtain in simulation, data latency in the flight system prevents us from exploring the higher bandwidth results we are able to obtain in simulation. Therefore, we are presently investigating hardware solutions for reducing latency.

Plans for Next Year

- Continue Implementation and evaluation of the adaptive neural net controller on the R-50 helicopter test bed, particular addressing the issue of data latency. This will also include closing outer loops that control velocity, flight direction and position.
- Continue to aggressively pursue rapid developing technology transfer opportunities, and leveraging with other NASA/Air Force/DARPA programs.

External Interactions

We have been collaborating with Guided Systems Technology (GST) for implementation and evaluation of our adaptive neural net controllers on the Yamaha R-50 helicopter.

Publications

Journals:

[1]Calise, A.J., Hovakimyan, N., and Idan, M., "Adaptive Output Feedback Control of Nonlinear Systems Using Neural Networks," Automatica, Vol. 37, No. 8, August 2001, pp. 1201-1211.

[2]Hovakimyan, N., Rysdyk, R. and Calise, A.J., "Dynamic Neural Networks for Output Feedback Control," International Journal of Robust and Nonlinear Control, November 2001, pp 23-39.

[3]Hovakimyan, N., Nardi, F., Calise, A.J., and Lee, H., "Adaptive Output Feedback Control of a Class of Non-linear Systems Using Neural Networks," International Journal of Control, Vo. 74, No. 12, December 2001, pp. 1161-1169.

Conferences:

[3]Johnson, E., Calise, A.J., "Neural Network Adaptive Control of Systems with Input Saturation," American Control Conference, Arlington, VA, June 25-27, 2001.

[2]Hovakimyan, N., Nardi, F. and Calise, A.J., "A Novel Observer Based Adaptive Output Feedback Approach for Control of Uncertain Systems," American Control Conference, Arlington, VA, June 25-27, 2001.

[4]Hovakimyan, N., Kim, N., Calise, A.J., Prasad, J.V.R. and Corban E., "Adaptive Output Feedback for High-Bandwidth Control of an Unmanned Helicopter," AIAA Guidance, Navigation, and Control Conference, Montreal, Canada, August 6-9, 2001.

[5]Calise, A.J., Hovakimyan, N. and Idan, M., "An SPR Approach for Adaptive Output Feedback Control with Neural Networks," Conference on Decision and Control, Orland, FL, December 4-7, 2001.

Ph.D. Theses:

Lee, Seungjae, "Neural Network Based Adaptive Control and its Application to Aerial Vehicles," April, 2001.